Gains and losses in hf aerials

by L. A. MOXON, BSc, CEng, MIEE, G6XN*

This article discusses the main factors which cause one aerial to be better than another.

Practical considerations dictate a gain figure of 5–6dB for most amateur hf beams but it is shown that, given a pair of comparable aerials, it is a simple matter to obtain about 3dB of extra gain by using both simultaneously.

Particular attention is paid to polarization and environmental differences, and the discussion has been extended to include the case of "lossy" aerials, leading to novel conclusions concerning the design of indoor, miniature and "invisible" aerials.

Part 1

AS pointed out in an earlier article [1] the gain of close-spaced two-element beams depends mainly on the ratio of phase-shift to spacing, since this determines the shape of the radiation pattern. It was also explained that subject to the practical limitations usually applicable to amateur hf beams, little or no extra gain is obtainable from additional elements. On the face of it this appears to leave little foundation for the popular belief that some beams are better than others, but a number of minimum requirements have to be met; in particular it must be possible to obtain the correct phase shift without incurring large current inequalities, and not all designs of beam provide for this. In most cases, moreover, there are environmental constraints of one sort or another and these may have considerable effect on the relative merits of different types of aerial.

Environmental extremes generate a variety of interesting problems; restriction on the use of visible aerials, for example, may require the use of indoor aerials, or very thin wire! In either of these cases losses may be quite large and if normal design procedures are followed, two elements may be worse for transmission than a single element. Detailed analysis suggests, however, that two elements should always perform better than one, subject to correct choice of design parameters and possible acceptance of some conflict between transmitting and receiving requirements. At the other extreme, in the absence of restrictions it may be possible to erect, say, a pair of rotary beams each with a gain of 5-6dB and obtain an average additional gain of 3dB by phasing them together; the necessary phasing and matching adjustments are surprisingly non-critical, and the system has been found to work well in practice.

Losses have also been studied in the context of trying to make beams as small as possible, leading to prediction of a minimum turning circle in the region of 7ft 6in radius for a low-loss 14MHz beam.

Single-element aerials

The lowest gain theoretically possible is that of an isotropic aerial which by definition radiates equally in all directions. All practical aerials radiate more in some directions than others and assuming the same total amount of radiated power they must, therefore, have gain in at least one direction relative to an isotropic radiator. In the case of a half-wave dipole this gain is 2dB, which is the maximum amount by which it would be theoretically possible to degrade its performance other than by losses. A very short but efficient dipole is only 0·4dB down relative to a half-wave dipole but worse performance can result from bending; for example, a dipole bent in the centre and viewed end-on appears as two elements in antiphase so that an "8JK" mode of radiation is produced in this direction.

If the bending process is continued to the point where both modes produce equal field strength, 29 per cent of the power is radiated in the "8JK" mode at right angles to the normal directions thereby resulting in a loss of 1·5dB, and this seems to be about the worst that can be achieved assuming that use is made of whichever mode produces the bigger signal. Typical of the worst elements likely to be used in practice is an inverted-V with a 90° apex angle, Fig 1, and it is obvious that this produces a fairly strong endwise groundwave field; assuming a separation of $\lambda/6$ between the "centres of gravity" of the two halves of the current distribution, this will be only about 6dB down on the dipole mode but, allowing for the 4dB gain of the "8JK" mode [1], the energy loss comes to only 10 per cent and the wanted signal is reduced by a mere 0·4dB.

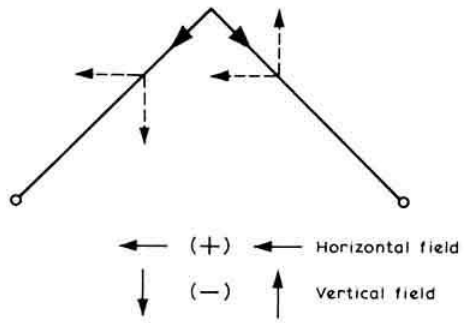


Fig 1. Inverted-V dipole showing resolution of field into horizontal and vertical components

* 1 Stonerhill House, Froxfield, Petersfield, Hampshire.

If two such elements are arranged as a beam, Fig 2(a), most of the endwise radiation will be cancelled and the performance will be virtually indistinguishable from that of straight (though somewhat shortened) dipoles. Similar figures apply to horizontal dipoles halved in length by bending the ends over at right angles.

The above examples give a broad general idea of what can be expected if one deliberately attempts to degrade the performance of a dipole by bending it into other shapes. The failure to achieve much success implies a high degree of freedom in the choice of element-shapes for coping with difficult mechanical or environmental problems, obviously a very important result.

To obtain appreciable gain relative to a dipole without using the antiphase (or "8JK") principle [1] it is necessary to have at least two separate concentrations of current separated by an appreciable fraction of a wavelength so that due to phase-differences the fields produced add more effectively in some directions than others. A single wire may be folded to form, for example, a collinear array of many elements, and the point at which it ceases to be regarded as a single element is an arbitrary choice, but for the present discussion an "element" is taken to be any radiator small enough to be generally useful as a 14MHz beam-element, although it may of course be used on its own.

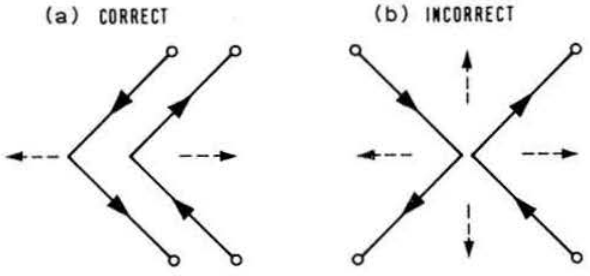


Fig 2. Two-element arrays using bent elements. Dotted arrows show directions of radiation with elements in antiphase. Gains with optimum phasing are roughly 5dB for (*a*) and 3dB for (*b*)

For this purpose the dipole has two main competitors, the quad and delta loops which can be considered together since the precise shape is of minor importance, though the operation of a quad loop is perhaps easier to visualize. In this case there are two concentrations of current separated by the width of the loop, usually a quarter-wavelength. It is usually reckoned that to obtain useful gain from two radiators they should be separated by at least half a wavelength, and it is more accurate to regard the quad loop as a *single* point source of radiation, more or less identical in performance with that of a dipole. Nevertheless this is only an approximation, and loops in fact provide an advantage of about 1dB over dipole elements; though insufficient in itself to have much effect on signal reports, this should not be discarded lightly since a major improvement in dx performance may be the result of several small improvements of this order.

Effect of ground

The discussion so far has ignored the presence of the ground. In the case of low-angle rays with horizontal polarization, all ground is virtually a perfect reflector. The aerial, with its image in the ground, can be treated as an "array" of two sources [2], and the radiation pattern in the vertical plane is obtained from the basic pattern for the aerial by multiplying it with the appropriate array factor which is *the same for all aerials at a given height and for a given angle of elevation*. The angle of elevation required for dx working is low enough to ensure that it would, in the absence of the ground, fall well within the vertical beam-width of practical amateur aerials so that the relevant part of the vertical-plane radiation pattern is *determined entirely by the array factor*; there is, therefore, no basis for the belief that one beam is better than another "because it lowers the angle of radiation".

At zero elevation above flat ground the direct wave and ground-reflected waves cancel each other since they are opposite in phase and have exactly the same distance to travel, but at any elevation-angle θ, the ground-reflected wave has to travel further by an amount $2h \sin \theta$, or approximately $2h\theta$ since we are interested only in small values of θ. Corresponding phase-shift is given in radians by $\frac{4\pi h\theta}{\lambda}$ and field strength by $2F_D \sin\left(\frac{2\pi h\theta}{\lambda}\right)$ as demonstrated by Fig 3.

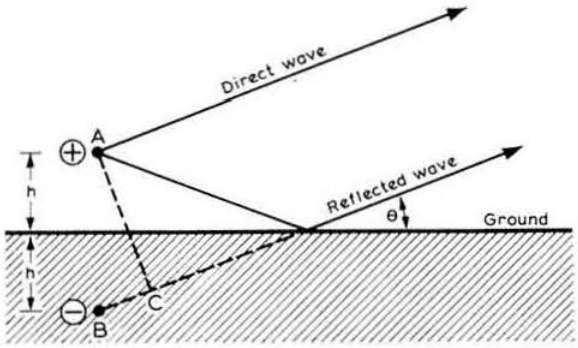


Fig 3. Derivation of array factor for horizontally polarized aerial and its image. The reflected wave has farther to travel, by the amount BC which is given approximately by $2h\theta$. The two waves arrive in phase at a distant point if $2h\theta = \lambda/2$, giving a field strength $2F_D$ where F_D is the corresponding free-space field

The appropriate value of θ depends on the particular dx path and the prevailing ionospheric conditions, any value up to 15° or so being likely, but there is some ground for regarding 6° as typical [3].

For this angle of radiation the array factor, and therefore the field strength for a given aerial current, is approximately proportional to height within the limits of normal amateur installations at frequencies up to 21MHz. There is a slight falling off from proportionality, to the extent of five per cent for a height of one wavelength and 10 per cent for 1·5 wavelengths. There are also slight variations, as plotted for the case of dipoles in Fig 4, which arise from changes in the mutual impedance between the aerial and its image; these in turn affect the radiation resistance and hence the aerial current.

With close-spaced beams the effect tends to be much reduced, as will be obvious for the case of two-element arrays in which each element "sees" a pair of images nearly opposite in sign and at almost the same distance. One result of this is

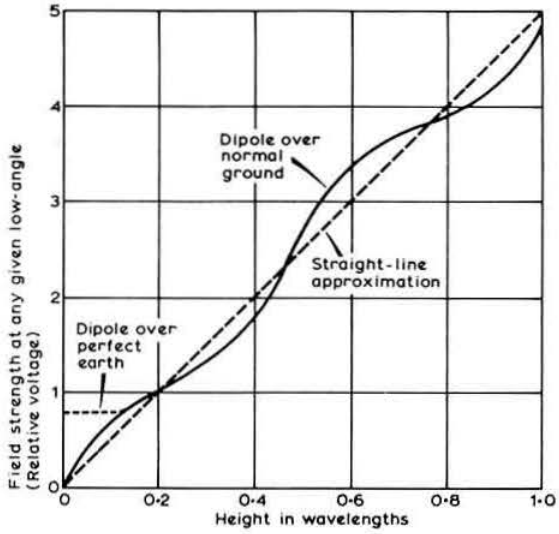
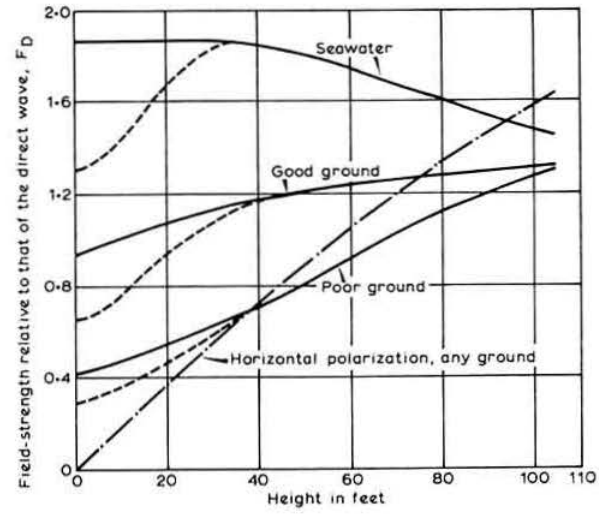


Fig 4. Effect of height on dx signal strength with horizontal dipoles. The ripples are attributable to variations in radiation resistance caused by mutual impedance between the aerial and its image, and are greatly reduced in the case of close-spaced beams



Vertical polarization, ground as indicated

Dotted curves indicate drop in signal-strength due to rise in radiation resistance of vertical elements at low heights above perfect ground. The drop may also be attributed to broadening of the vertical radiation pattern, the two effects being directly related.

Fig 5. Variation of field strength with height of aerial for 6° radiation angle at 14MHz

that the true gain of the beam relative to a dipole at the same height varies slightly with height, but it is, of course, the reference dipole, rather than the beam, which is varying.

In the case of vertical polarization with perfectly-conducting ground, the sign of the reflection coefficient is reversed so that the direct and reflected waves are in phase, and this has given rise to the belief that vertical aerials are good low-angle radiators. Unfortunately, in practice, losses in the ground cause the reflection coefficient to drop to a low value and change its phase at an angle of elevation known as the "pseudo-Brewster angle" from analogy with the behaviour of light waves. This angle varies between about 10° for "good" ground and 20° for "bad" ground, although it is much lower (about 3°) in the case of sea water.

For angles well below the Brewster angle there is little or no difference between horizontal and vertical polarization, but for an angle such as 6° the situation is rather more complicated. For this angle, Fig 5 provides a rough estimate of the likely variation of signal strength with aerial height for good ground, bad ground and over sea water, and also compares vertical with horizontal polarization. The solid curves assume a constant aerial current in a short vertical radiator and are based on data from [4] for the magnitude and phase of the reflection coefficient. The dotted curves take into account the rise in radiation resistance and consequent reduction of current due to the effect of the ground at low heights, assuming negligible loss resistance and perfectly-conducting earth.

The last assumption is an inconsistency, regrettably enforced by lack of data, but at worst the corrections will have been somewhat over-estimated. Curves for beam aerials can be expected to lie somewhere between the solid and the dotted lines. With lossy elements, eg a short inductively-loaded vertical whip, the solid line tends to indicate more closely the correct shape of the variation although the general level is reduced by the losses. The height is measured to the "centre of gravity" of the current distribution, or about one-twelfth of a wavelength above the feed point in the case of a ground-plane aerial with horizontal radials. The assumption of a "short element" is merely a device to allow the curves to be plotted down to zero height, instead of following the usual precedent of ignoring heights less than a quarter-wavelength. Important points to note include the following:

(a) At low heights for the stated angle of radiation, vertical aerials are always superior, though the claim that they are "good low-angle radiators" needs considerable qualification.

(b) The height below which vertical aerials are markedly superior at 14MHz varies from about 20ft with poor ground to 60ft with good ground.

(c) With increase of height from zero up to $\lambda/2$ the total change in performance with vertical aerials is only 3 to 6dB whereas the radiated field is almost directly proportional to height in the case of horizontal polarization.

(d) With poor earth the difference in performance between vertical and horizontal polarization is less than 2dB (or about half an S-unit) over a range of height from 20ft to 90ft.

With ground sloping in the desired direction it becomes much easier to achieve efficient low-angle radiation and possibilities arise of exploiting multiple reflections [3]. For gentle slopes there may be little to choose between horizontal and vertical polarization, but as the ground slope gets steeper the mirror image of a vertical aerial gets tilted back into the ground until at about 45° slope it becomes end-on to the required direction so that the field-strength is that of the

unmodified direct wave F_D. In contrast, horizontal polarization provides nearly the maximum possible field-strength $2F_D$ with heights of the order of $\lambda/4$ only. In the case of hilltop sites an intermediate situation arises, with increase of height causing the point of reflection to slide further down the slope thereby producing a disproportionate increase of signal strength. The following table has been calculated for an 11° slope having a flat top, with aerials in various positions.

TABLE

Distance of mast in feet from top of slope	Required mast height in feet for $F > 1{\cdot}6F_D$ at 6° radiation angle (14MHz)
On slope	36
25	40
70	56
00 (equivalent to no slope)	105

Calculations have been simplified by assuming reflection from a point, thus ignoring the requirements for Fresnel zones [3], but suffice to indicate general tendencies. The advantage of a hilltop site for omnidirectional working is obvious but the desirability for a given direction of locating aerials on the hillside rather than on the hilltop is rather less so, although it becomes much greater with increasing steepness, as demonstrated by the previous example.

Small beam aerials

It has been shown [1] that a gain of 5 to 6dB can normally be expected from hf beam aerials small enough to meet typical amateur needs. Unfortunately gain is easily lost through errors of design or adjustment and the safest procedure is to restrict the number of elements to two, one of them being parasitically excited and tuned for maximum gain. In the case of loop elements, which provide the higher of the two gain figures, the parasitic element must be tuned as a reflector, not as a director, and in all cases the spacing must be within certain limits, one-eighth wavelength being a safe choice. Instead of tuning for maximum gain, it may be more convenient to tune for a null on signals coming from directions of about 130° relative to the beam heading, as explained in [1]. The common practice of tuning for maximum back-to-front ratio sacrifices just over 1dB of gain, the reduction in interference received from the back direction being offset by the higher levels received from the 130° directions so that any apparent advantage is illusory.

The gain of quad or delta loop arrays cannot be effectively increased by adding a director owing to the very low value of current in the parasitic director when it is tuned for correct phasing, as explained in [1]. The use of a director and reflector, or two directors, can bring the gain of a dipole array up to equality with that of a quad, but it may be cheaper and easier, and will certainly be just as good, to raise the height of the smaller array by 10 per cent.

With two-element beams the basic requirements [1] for realizing the full gain potential are

(a) Phase-difference, relative to the antiphase or "8JK" condition, should be equivalent to about half that due to the spacing between the elements.

(b) Currents should be equal within about 20 per cent.

These conditions are normally met, but only just, with dipole arrays adjusted as described above. With reflector-type loop arrays the currents are more or less equal, causing deeper nulls which can often be used for getting rid of interference by making perhaps a small change in the beam heading; the greater design-margin also allows more latitude in the choice of spacing and this can be helpful in the design of multiband arrays.

Driven arrays

There are several popular designs of two-element beams in which both elements are driven. In principle the advantage of driving is that phase and amplitude can be adjusted independently so that spacing is less critical and deep nulls are obtainable in back directions even with dipole elements. Unfortunately the usual methods of phasing are based on the false assumption that "one eighth wavelength of line equals 45° of phase shift" which is true only if a perfect match exists *at the elements*, whereas phasing, matching and current-ratio are all critically interdependent. Since the radiation resistance [1] is in the region of 15Ω, for maximum gain with dipole elements a matching device (eg T or gamma match) is essential, and this is usually not provided.

The best-known example of this type of array is probably the ZL Special, Fig 6, for which the *ARRL Antenna Book* [5] quotes a gain of 3-4dB, implying a phase shift somewhat greater than the "design target" of 45°, which is in any case excesssive as discussed above. (Alternatively the low gain could be the result of considerable current inequality but this seems less likely in view of the good back-to-front ratio usually experienced). Referring to the design curves, Fig 7, reproduced from [1], the characteristics of the ZL Special appear consistent with operation in the region $\phi/\phi_0 = 1{\cdot}2$ to $1{\cdot}6$, for which the adjustments are relatively non-critical and the variables tend to be largely self-compensating; thus an excessive value of phase shift increases the radiation resistance which brings the dipoles closer to a matched condition and reduces the phase shift.

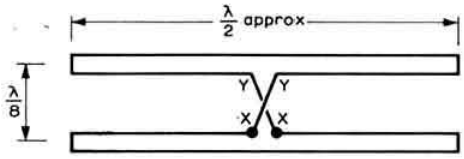


Fig 6. This illustrates the principle of the ZL Special. Open wire line may be used for the elements and for the phasing line XY. In one version the aerial is fed with low impedance twin line at XX. Variations include the use of 300Ω twin line throughout, and unequal element lengths

Other popular designs are based on the use of two separate feeders of equal length plus an additional length, usually $\lambda/8$, which is used as a phasing line. This permits operation at any desired point on the curves of Fig 7 but only if the feeders are matched at the elements or if the complete system is resonant, eg half-wave elements with an even number of half-wavelength of feeder between them inclusive of the phasing line. The importance of satisfying these requirements is not always appreciated and inspection of several popular designs suggests there will almost certainly be some loss additional to the usual decibel or so incurred by

adjusting for maximum "nominal" front-to-back ratio. The matched-feeder procedure is often difficult to apply since any adjustment of the phasing line requires re-matching at the elements and all adjustments are interdependent; on the other hand, the resonance method ensures equal element currents since, looking into any point on the loop of feeder between the elements, any reactance visible when looking in one direction is equal but of opposite sign to the reactance visible in the other. It is assumed for the purpose of this explanation that the radiation resistances are equal, which is only true if the mutual impedance is non-reactive, ie for an element spacing of $\lambda/8$, but reactive effects can be compensated by alteration of feeder length.

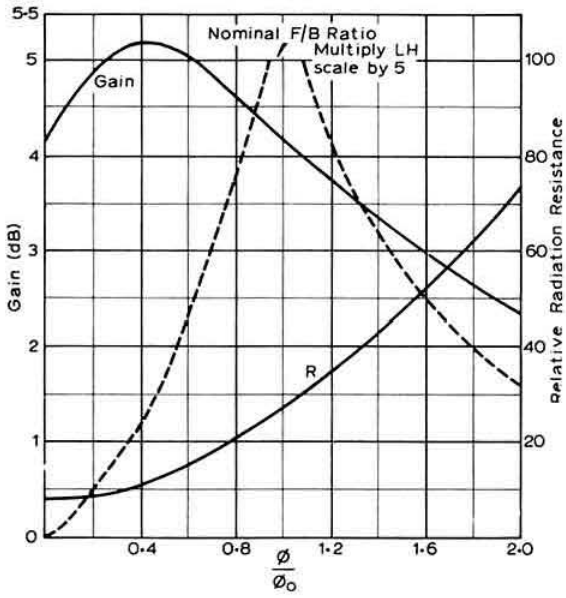


Fig 7. Variation of gain, radiation resistance and front/back ratio with ϕ/ϕ_0. Resistance scale is correct in ohms for each of a pair of dipoles spaced $\lambda/8$ (equal currents are assumed)

In either case the phase-shift is different from the electrical length of the phasing line, and it will probably be obvious to the reader that this is the "$\pm$X" method of phasing which was assumed in the appendix to [1] for the purpose of simplifying the basic theory of close-spaced two-element beams in general. It lends itself particularly to the use of resonant feeders as shown in Fig 8; starting from resonance a small displacement of the feedpoint either side of centre is equivalent to the insertion of equal and opposite reactances of about $4f\Omega$/foot, where f is the frequency in megahertz. This arrangement allows multiband operation subject to adjustment of feeder length although, like other resonant-feeder systems, it is somewhat frequency sensitive; this tends to show up as current-inequality at the band edges but acceptable results have been obtained over the full width of the 14MHz phone band with folded-dipole elements and half-wave feeders. This aerial works equally well on 21MHz subject to shortening the feeders by about 42in, the feedpoint displacements being about 30in and 10in on 14 and 21MHz respectively relative to the centre of the system.

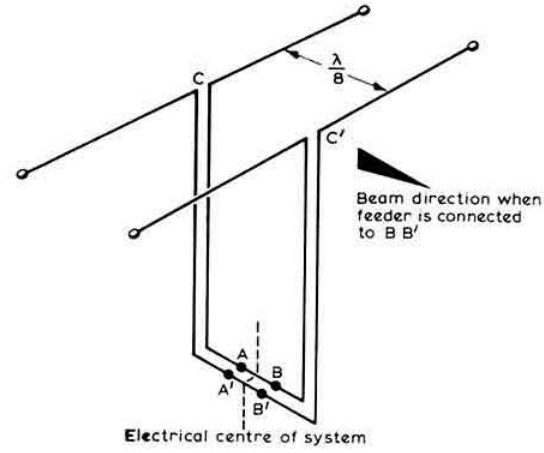


Fig 8. Two-element driven array with mismatched feeders. If the elements are resonant ($\lambda/2$) the length CABC′ must be an even number of half-wavelengths. AB is the phasing line and is much less than $\lambda/8$ if open-wire lines are used. Note that the feeders are crossed over as for the "8JK" aerial

An equivalent method of phasing is used in the "Swiss Quad", where it takes the form of differences in the loop sizes [6].

Compatability of element shape

When elements bent into "abnormal" shapes are assembled into a beam, particular care is needed to ensure that unwanted modes are suppressed and not reinforced. This is most likely to be achieved when the elements have similar shapes and orientation. Fig 2 shows two ways of arranging a pair of V-shaped elements with right-angled bends and it will be noticed that in case (a) with antiphase excitation, the endwise radiation is completely suppressed, whereas in case (b) there is complete symmetry, producing radiation of equal strength in all four directions. This implies a loss of exactly 3dB, although this is reduced to about 1dB with 45° of phase-difference, so that the maximum gain obtainable from an X-configuration appears to be in the region of 3dB. The loss of 2dB must, of course, be weighed against possible mechanical advantages, and will be fully recovered if these enable the mean height to be increased by 25 per cent. Similar arguments often apply to other methods of making beams smaller or more convenient to erect.

To be continued

Next month.....

Part 2 of this article continues the analysis of hf aerials and looks at:

- ★ **small beams**
- ★ **high-loss beams**
- ★ **measurement problems**

Plus "breaking the gain barrier"

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Part 2

Small beams

The length of a dipole or a beam element may be reduced to any desired extent without appreciably affecting its radiation pattern, but in the process the radiation resistance drops rather rapidly to a point where it becomes comparable with the losses, which may be estimated with the aid of Fig 9 if the aerial is sufficiently "in the clear" for dielectric losses to be neglected. Thereafter the effective transmitting gain starts to decrease and rapidly becomes unacceptable. Usually, before this point is reached the bandwidth has narrowed to a value which causes some inconvenience.

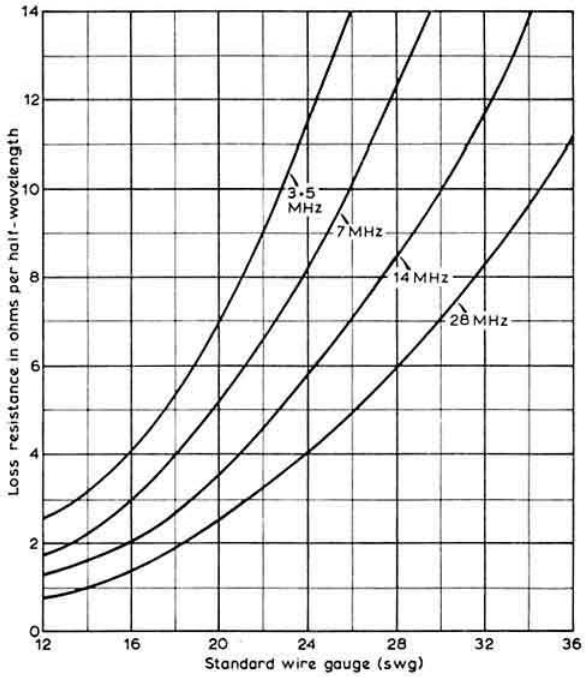


Fig 9. RF loss resistance of thin copper wires. Uniform current distribution assumed. Divide by two to obtain the effective loss resistance referred to a current maximum for the case of a sinusoidal distribution

When a dipole is shortened it must be loaded in some way to bring it back into resonance and there are basically two methods, inductive loading by a coil or stub in the centre or capacitive loading at the ends, Fig 10. In the case of the inductive stub, the dipole has merely been folded in the middle, keeping the total length of wire and therefore the loss resistance more or less constant, though in practice the length has to be increased somewhat and there is some "transformer action" in the stub which further increases the losses. To simplify the discussion these effects will be ignored and the reader should merely note that estimates based on Fig 11 for the inductive case will be slightly optimistic.

Fig 10(b) illustrates probably the simplest form of capacitive loading with the end wires providing capacitance to ground; currents flow in these wires but in opposite directions so they have negligible effect on the radiated field. The amount of loading required can be estimated *very* roughly, provided the loading wires are well removed from resonance, by taking 3ft of end-wire as equivalent to 2ft of radiator. More loading can be obtained by any device which increases the "concentration of metal" at the ends of the radiator, eg pairs of wires in the form of a cross, or by increasing the diameter of the loading wires relative to that of the radiator.

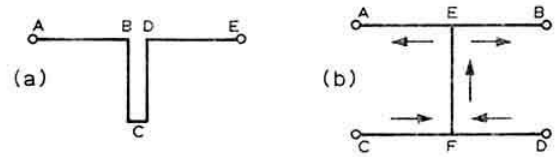


Fig 10. Methods of loading short dipoles: (*a*) Inductive loading; for resonance AB + DE + 0·75(BCD) ≏ λ/2. (*b*) Capacitive loading; arrows indicate current directions. For resonance 0·67 (AB + CD) + EF ≏ λ/2.
Formulas very approximate in both cases, depending on wire gauges and dimensions. In (*a*) the stub BCD may be replaced by a coil. Sometimes the two methods are combined, eg by using coils near the ends of a dipole

As illustrated by Fig 11, capacitive loading allows the use of very much shorter elements for any given low value of radiation resistance, and the loss-resistance is also reduced thus allowing the erection of an efficient beam in very limited space. Compared with inductive loading, the end-voltages will be much lower, allowing closer proximity to other objects although this advantage is partly offset by the risk of greater capacitive coupling to these objects. There are some snags, however, a point being reached where reduction in length of radiator is more than offset by the increased length of the loading conductors, and in general despite the shorter elements the total top-weight of a beam is increased by this form of loading.

The possibilities and some limitations of this type of element are illustrated by the following examples:

(a) A 14MHz beam was formed from two 15ft horizontal elements supported between four polythene-cord guys each having a 15ft copper-wire insert near the top, end loading being provided by these inserts. Performance at a height of 35ft showed only a very slight drop in average

* 1 Stonerhill House, Froxfield, Petersfield, Hampshire.

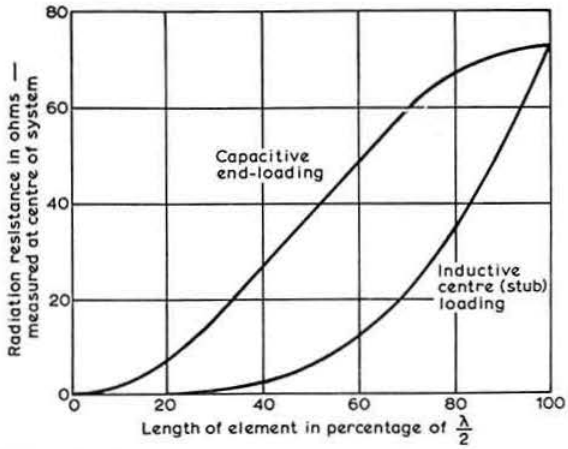


Fig 11. Radiation resistance of short dipoles with alternative methods of loading. For beams designed on the guide-lines of Fig 7, the radiation resistance varies with length of element in the same ratio as that of single dipoles

signal reports from VK, compared with a quad at 50ft, and provided the first evidence of a small site-superiority estimated as about 2dB from later tests with other aerials at a greater height.

(b) A vertical beam [3] was constructed for 7MHz using 25ft vertical elements as in Fig 10(b), end-loaded by 30ft lengths of horizontal supporting wires. Further reduction in height was prevented by the requirement for not more than $\lambda/4$ spacing between elements, the maximum usable lengths for the loading wires being equal to the spacing.

(c) A design for a 14MHz beam used 10ft wire elements end-loaded by 4ft crosses of 0·5in diameter tubing. Although the element-length was only 10ft, the total distance back-to-front with 8ft spacing was 12ft. Any further reduction in length would have required more loading, thus increasing back-to-front dimensions, and it was estimated that an 11ft square design would probably be optimum, giving a required turning circle of just over 15ft diameter. The radiation resistance (estimated for $\phi/\phi_0 = 0{\cdot}5$) for each element was 3·5Ω, the loss resistance (12 swg) was 0·36Ω, and the estimated bandwidth was of the order of 125kHz. Though not yet tried in practice, this example is thought to be realistic and one American manufacturer has produced a beam with very similar dimensions. It is thought they cannot be further reduced without significant loss of gain.

In contrast it appears unlikely that elements such as Fig 10(a) could be reduced below about 24ft length for a two-element beam without serious restriction of bandwidth and loss of efficiency.

High-loss beams

An interesting problem arises if, for any reason, it is necessary to use inefficient elements, a situation likely to arise, for example, when there are restrictions on the erection of visible aerials. A thin wire trailing over a wet tiled roof, or even a thicker wire just inside the roof space, clearly breaks all the rules of good aerial design, and resistance losses may be greatly augmented by losses in brickwork or other poor-quality insulating materials. But the situation is by no means hopeless, remembering that even a few watts of effective radiated power is capable of providing regular dx contacts. For reception, owing to the high external (galactic) noise level, a large number of decibels can be sacrificed without adverse effect on signal-to-noise ratios and, however great the losses, unidirectional patterns identical with those of typical high-quality beams may be achieved by the use of two or more suitably-phased elements, although a completely different set of design requirements arises.

These may be derived from calculations on similar lines to those in [1] by adding a relatively large loss resistance R_L to the radiation resistance R, the phase-shift due to a series-reactance X being given approximately by X/R_L which bears no relation to the previous formula $X/(R + R_m)$. Because of the assumed high value of R_L very little current flows in a parasitic element so *both elements must be driven*. Much higher values of reactance X are required to produce a given radiation pattern, but alternatively phasing-lines may be used without any of the complications described earlier since the mutual impedances which give rise to them are negligible in comparison with the loss resistance. The mathematics are actually very much simplified and it is easy to divide the power equally between two elements so that, if a current I would flow in one element alone, equal currents 0·707I flow in each of the two elements. With $\lambda/8$ spacing and 135° phase-difference (ie $\phi/\phi_0 = 1$) the field strength "in the beam" is identical with that from a single element and is only a fraction $R/(R + R_L)$ of that which would be produced by an efficient dipole, although the radiation pattern is the same as that of an efficient beam having the same spacing and phasing. 3dB improvement in the radiated signal may be obtained, however, by driving both elements in phase, which destroys the front-to-back ratio, so there is a conflict between transmitting and receiving requirements.

Fig 12 compares the variation of gain with phase angle for low-loss elements, the extreme lossy situation discussed above and two intermediate cases, the low-loss curve being an extended version of that shown in Fig 7. Front-to-back ratio is also plotted, over the range of main interest for the case of lossy elements. It will be noticed that losses cause the maximum of the gain curve to shift to the right, the loss of gain due to "incorrect" phasing being more than offset by the increase of efficiency due to higher radiation resistance as one moves further away from the antiphase condition. For the same reason it would be advantageous, in the intermediate cases only, to use wider spacings. It is notable that with wide spacings, compared with a single lossy element, 3dB gain always exists in some directions and these can be varied at will, depending on the phase-shift.

Indoor and some other "invisible" kinds of aerial might be expected to fall somewhere in the intermediate region, and the curves demonstrate the extreme unsuitability of the "8JK" aerial in such situations.

Breaking the "gain barrier"

Earlier in the article 6dB was quoted as an upper limit for the gain of hf beams, subject to the practical limitations which usually apply to amateur hf operation. Apart from special-purpose fixed-arrays, some 14MHz rotary beams with appreciably higher gain are in existence, but these are massive engineering projects beyond the resources of most amateurs. An additional 2-3dB gain may be obtained on 28MHz by building a beam the same size as a conventional 14MHz array, but it is usually difficult to accommodate both and such arrangements are used infrequently. Vertically-stacked

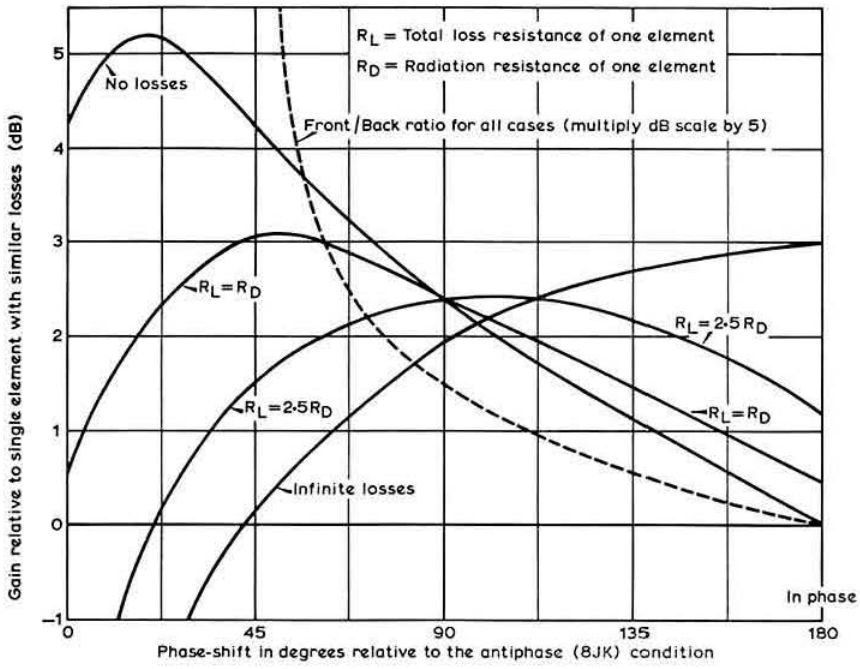


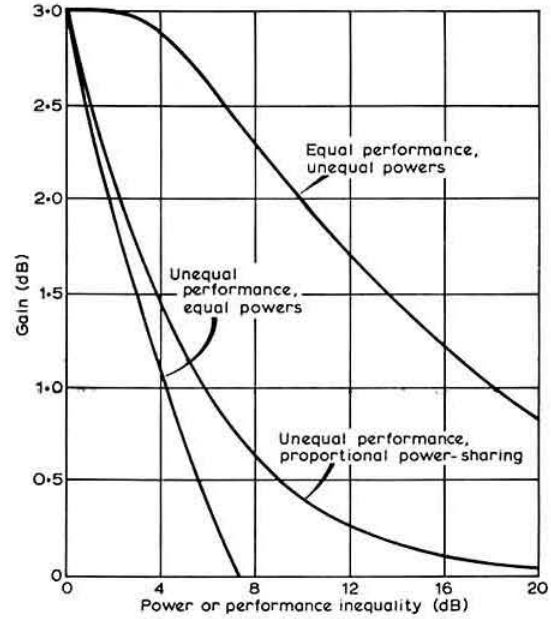
Fig 12. Gain and front/back ratio for a pair of lossy elements spaced $\lambda/8$. The elements are assumed to be driven with equal currents. Gain or loss relative to a loss-free dipole is obtained by subtracting the loss-figure $10 \log_{10}(1 + \frac{R_L}{R_D})$ from the gains indicated

Fig 13. Gain from combination of two aerials. When the aerials differ in performance, gain is relative to the best aerial alone and is maximum when power is shared in proportion to the performance, with the best aerial receiving most power. Both aerials are assumed to have the same polarization

arrays are sometimes feasible on 28MHz and can give useful extra gain if the height is sufficient, but vertical stacking reduces average height and at 14MHz this usually neutralizes any extra gain.

In fact, the "gain barrier" can be raised considerably at 28MHz since the use of resonant feeders (at least as far as a point within reach of the operator) provides a simple and efficient method of exploiting the full gain potential of 14MHz-sized elements on three bands. There are some mechanical difficulties with the feeder if 360° rotation is required but it is possible with two feeders to make the beam reversible so that less than 180° rotation is needed; moreover the facility of instantaneous beam-reversal can be a major advantage. Another method of using the whole of each element on each band [7] employs matching networks switched by relays at the aerial, but this might be expected to involve maintenance problems in many cases since it involves a complex unit which would not always be readily accessible.

There is one method of obtaining extra gain which, it is felt, deserves to be more widely known although it requires additional space and might sometimes add to difficulties with neighbours or planning authorities; it consists of the employment of two separate beams with appropriate phasing and provides an average improvement of 3dB, assuming spacings of half-a-wavelength and upwards. Adjustments are surprisingly non-critical, and random phasing, subject to an optional phase reversal with no attempt at equalizing the powers fed to the beams, is sufficient to ensure gains of more than 2dB in two cases out of three. Assuming correct phasing (within about 45°) even a 10 : 1 power inequality only reduces the gain by 1dB. A correctly-set four-position phasing-switch is sufficient to ensure that the gain is never less than 2·4dB (usually much closer to 3dB) and it could, if desired, be linked automatically with the beam heading. The aerials are assumed to be connected in parallel



with additional quarter-wavelengths of feeder brought into circuit as required. With twin feeder a single length of switched phasing line, with phase reversals, provides the required minimum of four options.

The above argument assumes, of course, that the two aerials are equally efficient. However bad one of them may be, there must always be some gain provided the aerials are similarly polarized and the power is shared between them

in proportion to their efficiency. Unfortunately, if one aerial is much worse than the other the extra gain is infinitesimal. Fig 13 shows gain as a function of the power sharing ratio for aerials of equal and unequal performance.

If the aerials are spaced by only half a wavelength there will be about $\pm$1dB variation of gain caused by mutual interaction but this rapidly diminishes with increased spacing.

If miniature beams are used it is important to note that this has no effect on the spacing requirement, ie a minimum of half a wavelength.

Other losses, and a few measurement problems

The rest of this article is mainly the saga of three aerials. The first, after producing a number of flattering reports, was found to be down on No 2 by an amount which was large compared with most of the gains or losses hitherto discussed. The second, in its turn, gave such a bad account of itself in comparison with No 3 that at first a feeder short was suspected. Nos 1 and 3, being fixed beams in different directions, could not be compared directly.

Resolution of this paradox was highly instructive, proving that 44 years of experience is no safeguard against surprises or, as the less charitable may suggest, elementary mistakes. No 1 was fed with coaxial cable and showed a particularly low value of swr which should have given and eventually did give cause for suspicion, particularly as, although the aerial was designed on the lines of Fig 8, the swr was not critically dependent on the position of the feedpoint which should have altered the radiation resistance as indicated by Fig 7.

In contrast, No 2, of similar design but fed with open-wire line, behaved as expected. The measured loss in the coaxial feeder was only 1dB and this tended to allay suspicion until it was found that the swr measured at the first aerial instead of at the transmitter behaved in the same way as that of No 2 aerial. No balun was used, in view of several previous experiments in which they had not been found necessary. Nevertheless, replacement of the coaxial cable by open-wire line completely removed the difference in performance and there can be no doubt that the initial high loss and low swr were fully accounted for by feeder radiation. The need for a balun when using coaxial feeder depends on feeder length as well as several more complex factors, and clearly the safest course is to use one at all times.

The poor result with No 2 applied only to one direction, that of No 3, and was due entirely to screening by No 3 despite a separation of about 1·5λ and reasonably good front-to-back ratios. Usually much smaller separations are adequate, but the result was explainable theoretically on the following grounds:

(a) The front-to-back ratio of a beam applies to signals at its input terminals, and not to its properties as a re-radiator of stray fields.

(b) Over short distances the ground reflected wave has to travel considerably further than a wave parallel with the ground, so that reinforcement can take place even though the angle of radiation is nominally zero. It is thought that, at least, the parasitic reflector of No 3 was being energized rather efficiently in this manner and producing a field in antiphase with the radiation from No 2 in this direction.

The effect of removing No 3 was very obvious on a field-strength meter and about two S-units in terms of signal reports. By focussing attention on the ground-reflected wave, this episode underlines one of the many difficulties in the making of gain measurements, namely the different role played by ground and other local reflections in the case of ground-wave propagation, particularly at short ranges, as compared with their effect on sky-wave propagation. Also, by implication, it highlights the risk of screening by power and telephone wires, and where such danger exists it would appear advisable to make comparative tests between temporary horizontal and vertical radiators at appropriate heights and positions before investing heavily in a permanent beam installation. It is obvious that little reliance can be placed on gain measurements using ground-wave signals, and even conclusions based on signal reports can be misleading unless any other aerials in the vicinity are either end on, dismantled, or in some way detuned from resonance. As a corollary to this it should be noted that when beams having separate feeders for different frequencies are stacked on a common mast, the driven elements not in use will have several resonances which depend on the feeder length, and one of these can easily coincide with the wanted frequency with disastrous consequences; the possibility of this can easily be checked by short-circuiting unused feeders and, if necessary, altering their length to avoid unwanted resonances.

References

[1] L. A. Moxon, "Supergain aerials", *Radio Communication* September 1967.

[2] *Radio Communication Handbook*, fourth edition, p13.41.

[3] L. A. Moxon, "Low angle radiation", *Wireless World* April 1970.

[4] F. E. Terman, *Radio Engineers' Handbook* 1943, pp700-707.

[5] *ARRL Antenna Book*, 12th edition, 1970.

[6] R. A. Baumgartner, HB9CV, "The Swiss quad beam aerial", *RSGB Bulletin* June 1964.

[7] E. R. Shepherd, ZL2ASJ, "The '663' beam", *73* June 1970.

Erratum—In Fig 1 the current should be shown flowing from left to right, not outwards to left and right from the centre.

Appendix

Derivation of gain figure for combination of two aerials

If one aerial is given a fraction x of the available power, the other receives $(1 - x)$.

The field-strength at a given distant point is therefore proportional to $\sqrt{x} + \sqrt{1 - x}$ assuming that both contributions arrive in phase. This is the relation which is plotted as the upper curve of Fig 13, the optimum condition being $x = (1 - x)$, ie equal power is fed to both aerials.

If the second aerial is n times less effective, in terms of signal power, than the first, the second term becomes $\sqrt{(1 - x)/n}$. Putting $x = (1 - x)$, ie $x = 0{\cdot}5$, this gives the lower curve of Fig 13.

By differentiation of the expression $\sqrt{x} + \sqrt{(1 - x)/n}$ we find that maximum field strength is obtained when $x = n/(1 + n)$, ie when the aerial which is n times better is given n times more power. Substituting this value for x, we find that with proportional sharing the field strength produced is proportional to

$$(1 + n)^{1/2} (n^{1/2} + n^{-1/2}).$$

This gives the middle curve of Fig 13.